

A DETECTION OF MOLECULAR GAS EMISSION IN THE HOST GALAXY OF GRB080517

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ABSTRACT

We have observed the host galaxy of the low redshift, low luminosity GRB080517 at 105.8 GHz using the IRAM Plateau de Bure interferometer. We detect an emission line with integrated flux $S\Delta\nu = 0.39 \pm 0.05 \text{ Jy km s}^{-1}$ – consistent both spatially and in velocity with identification as the J=1-0 rotational transition of carbon monoxide (CO) at the host galaxy redshift. This represents only the third long GRB host galaxy with molecular gas detected in emission. The inferred molecular gas mass, $M_{\text{H}_2} \sim 6.3 \times 10^8 M_{\odot}$, implies a gas consumption timescale of $\sim 40 \text{ Myr}$ if star formation continues at its current rate. Similar short timescales appear characteristic of the long GRB population with CO observations to date, suggesting that the gamma-ray burst in these sources occurs towards the end of their star formation episode.

Subject headings: galaxies: individual(GRB Host 080517) – gamma-ray burst: individual(GRB080517)
– radio lines: galaxies

1. INTRODUCTION

Long Gamma-Ray Burst (GRB) host galaxies are selected out by the explosion that is believed to mark the end of the life of a massive star (e.g. Woosley & Heger 2006). Given the short lifetime of such stars, it is unsurprising that the vast majority of host galaxies to date have been identified as star forming (e.g. Savaglio, Glazebrook, & LeBorgne 2009; Svensson et al. 2010) and are predicted to be rich in molecular gas (Draine & Hao 2002; Draine 2000). The absence of absorption signatures in the afterglows of bursts, illuminating molecular gas along their line of sight out of their host galaxy, has thus caused some concern. Initial investigations (e.g. Vreeswijk et al. 2004; Ledoux et al. 2009) revealed a shortage of detections in the H₂ Lyman-Werner bands relative to those expected. Unusually low metallicity, low dust content conditions, preventing the formation of molecules on the surface of dust grains, have been invoked as a possible explanation (Ledoux et al. 2009; Tumlinson et al. 2007). While a handful of GRBs have since been identified with molecular absorption signatures in their afterglows (Prochaska et al. 2009; Krühler et al. 2013; D'Elia et al. 2014; Friis et al. 2014), these observations are difficult and require sensitive spectroscopy probing the rest-frame ultraviolet.

In an alternative approach, a number of GRB host galaxies have been targeted for observations of direct emission from carbon monoxide in the far-infrared rotational transitions. Assuming a conversion factor, derived from local resolved star formation, this can be

used as a proxy for the presence of molecular hydrogen (see Solomon & Vanden Bout 2005, and references therein). Early observations targetting the host of low redshift GRBs 980425 (Hatsukade et al. 2007, $z = 0.0085$) and 030329 (Endo et al. 2007, $z = 0.17$) yielded non-detections, as did observations of the higher redshift host galaxies of GRBs 000418 (Hatsukade et al. 2011, $z = 1.1$) and 090423 (Stanway et al. 2011, $z = 8.2$). It is only recently that observations with the highly sensitive Atacama Large Millimeter Array (ALMA) secured a detection of carbon monoxide emission in the hosts of GRBs 020819B and 051022 (Hatsukade et al. 2014, $z = 0.41$ and 0.81).

We have recently identified the host of GRB080517 as an example of an unusually low redshift ($z = 0.089 \pm 0.003$) GRB host galaxy, with evidence for a mature stellar population underlying an ongoing star formation episode (Stanway et al. 2014). The host galaxy is accompanied by a neighbouring galaxy, sufficiently close in velocity and projected distance to plausibly be interacting with it. In this Letter we present observations targetting the J=1-0 rotational transition of carbon monoxide in this system².

2. OBSERVATIONS

Observations, centered on the X-ray location of GRB080517 ($06^h 48^m 58.03^s +50^\circ 44' 07.7''$, 90% error radius $1.5''$), were undertaken at the IRAM Plateau de Bure Interferometer (PdBI) on 2014 Jun 09 and 2014 Jun 11. The WideX correlator was used to probe a

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3.6 GHz bandwidth centered at 105.8 GHz, the expected frequency of the CO(1-0) transition at the target redshift, at 2 MHz resolution. Data were collected by observatory staff and scheduled across hour angles ranging from -4.1 to 1.2h to ensure good uv -plane coverage. A total integration time of 72 minutes was achieved on target. The array was in the compact 5Dq configuration, with five antennae in use. The resulting synthesized beam had a full-width at half-maximum (FWHM) of $5.7 \times 4.4''$ and the half-power width of the PdBI primary beam at this frequency is $48''$. Bandpass and flux calibration was performed on 3C454.3, yielding an estimated systematic uncertainty $<10\%$. Phase calibration was performed with reference observations of QSO B0714+457, which has a flux of 0.2 Jy at these frequencies, taken at regular intervals throughout the science observing. Data were reduced and calibrated using standard tools in the GILDAS data reduction package, and were imaged using natural weighting.

A flux excess was observed in the resulting data cube at the pointing centre and target frequency. We extract spectral information from a spatial region corresponding to 1.5 times the synthesized beam. The centre of this aperture is located at the optical position of the GRB080517 host galaxy (i.e. within $2''$ of the pointing centre). As figure 1 illustrates, the resulting spectrum shows a clear emission line centred at 105.790 GHz. This corresponds to $z = 0.08962 \pm 0.00003$ if the line is identified, as we expect, as the CO J=1-0 rotational transition with a rest-frame frequency of 115.271 GHz.

We re-imaged the data, integrating those channels contributing to the line, yielding a total bandwidth of 40 MHz (113 km s^{-1}). The resulting image (figure 2) reveals an isolated source located coincident with the optical centre of the GRB host galaxy. Deconvolution with the synthesized beam yields a marginally resolved source with FWHM $2.0 \times 2.5''$, consistent with the $1.7''$ Sersic radius measured in the optical (although with considerable uncertainty since this source is well below the size of the synthesized beam).

The observed emission line has a peak flux $7.7 \pm 1.7 \text{ mJy}$, measured in a 4 MHz channel. A gaussian fit to the observed line yields a full-width at half maximum of 76.5 km s^{-1} and an integrated line flux $S\Delta\nu = 0.39 \pm 0.05 \text{ Jy km s}^{-1}$ (a 7σ detection). A possible second velocity component is observed at a velocity offset of $\sim -170 \text{ km s}^{-1}$, but at too low a significance to be considered a detection ($\sim 2\sigma$). No 2.8 mm continuum flux is detected from the GRB host galaxy to a 3σ limit of $0.4 \text{ mJy beam}^{-1}$ in a map constructed from line-free channels, with a total bandwidth of 3.4 GHz.

The neighbouring galaxy described in Stanway et al. (2014) is offset from the GRB host by $16''$ and $\Delta v = 576 \pm 155 \text{ km s}^{-1}$, allowing us to simultaneously constrain it with this data. Neither line nor continuum flux is detected from the neighbouring galaxy to the limits of the data. We note that one component of the neighbour (Component B in Stanway et al 2014) is coincident with a 2σ peak in the continuum flux map, accounting for primary beam attenuation at the galaxy location (a factor of 0.65). However other peaks of comparable or greater statistical significance have no optical-infrared counterpart, suggesting that this may well be coincidence with

correlated noise in the map.

3. INFERRED QUANTITIES

We convert the integrated line flux obtained above to a CO luminosity³. The resulting line luminosity, $L'_{\text{CO}} = 1.5 \times 10^8 \text{ K km s}^{-1} \text{ pc}^2$, corresponds to an inferred molecular gas mass, $M_{\text{H}_2} = \alpha L'_{\text{CO}} = 6.3 \times 10^8 M_{\odot}$ for the Galactic conversion factor $\alpha = 4.3 M_{\odot} / (\text{K km s}^{-1} \text{ pc}^2)$ (Bolatto et al. 2013; Prochaska et al. 2009). This amounts to only 15% of stellar mass derived from spectral energy distribution fitting (Stanway et al. 2014) and potentially less if the $\alpha = 0.8$ conversion factor appropriate for densely star forming systems such as ULIRGs is more appropriate.

Given a measured luminosity in the CO(1-0) line, we can estimate the likely far-infrared luminosity, assuming that the host galaxy follows the well-established (see Solomon & Vanden Bout 2005, and references therein) correlation between these quantities. The inferred $L_{\text{FIR}} = 2 \times 10^{10} L_{\odot}$ would correspond to a predicted 105.8 GHz continuum flux of just $8 \mu\text{Jy}$, assuming a modified blackbody with dust temperature 35 K and emissivity index $\beta = 2.0$, consistent with our non-detection in the continuum. Given this modified blackbody spectrum, the predicted submillimeter flux at $850 \mu\text{m}$ (350 GHz) would be $S_{850} = 0.8 \text{ mJy}$, challenging but within reach of the current generation of instruments.

Interestingly, we can compare this prediction for the submillimeter luminosity with estimates based on earlier observations. The H α and $22 \mu\text{m}$ -continuum derived star formation rate of $\sim 16 M_{\odot} \text{ yr}^{-1}$ (Stanway et al. 2014) would lead to a predicted thermal infrared luminosity $L_{\text{FIR}} \sim 10^{11} L_{\odot}$, while the radio continuum emission detected at 4.5 GHz would suggest a thermal infrared luminosity $L_{\text{FIR}} \sim 6 \times 10^9 L_{\odot}$ (using conversions from Kennicutt & Evans 2012). The estimate from the carbon monoxide line emission is bracketed by these alternate estimates. Given that each conversion from flux to star formation rate is associated with a $\sim 30\%$ error, and that the scatter in the L'_{CO} - L_{FIR} relation is ~ 0.5 dex, these results show broad agreement, producing a coherent picture of the emission from ongoing star formation and its associated gas supply within the GRB080517 host galaxy.

4. DISCUSSION

Detections of GRB host galaxies in molecular gas are rare, at least in part because of the difficulty of such observations, but the remarkable feature of the host of GRB080517 is not its detection, but rather that the emission is so weak. The inferred molecular gas mass in the GRB host represents less than 20% of the stellar mass derived from its optical and near-infrared continuum flux. While this gas fraction is not, in itself, unusual, in combination with the galaxy's star formation rate it presents an anomaly.

The on-going star formation rate in the host galaxy of GRB080517 is higher than typical for its stellar mass and suggests that it will burn through its available supply of molecular gas in $\sim 40 \text{ Myr}$, assuming 100% conversion of gas to stars. More conservative estimates for the

³ adopting a standard $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M=0.3$, $\Omega_{\Lambda}=0.7$ cosmology

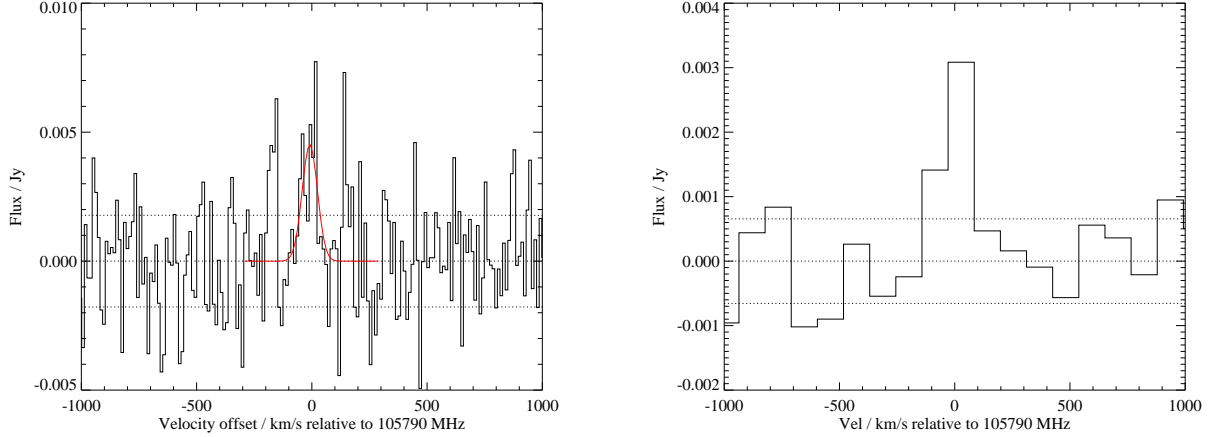


FIG. 1.— The spectrum of GRB Host 080517 at velocity resolutions of 4 MHz (left) and 40 MHz (right). Spectral information is extracted from a spatial region corresponding to 1.5 times the synthesized beam, located at the position of the GRB 080517 host galaxy. We measure a flux excess at the expected frequency of the CO (1-0) rotational transition. Dotted lines indicate the root-mean-square noise level.

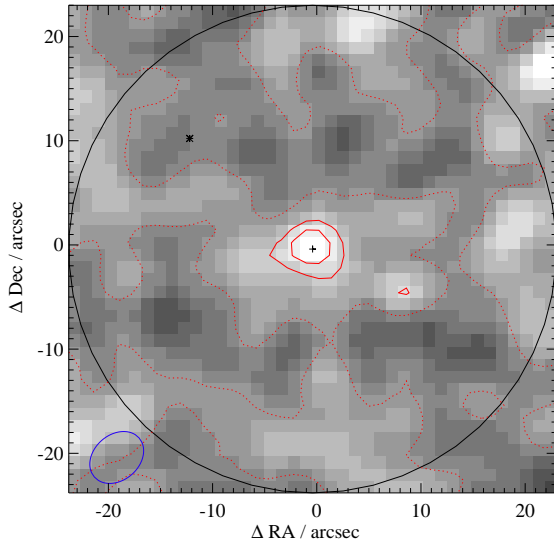


FIG. 2.— The CO emission from GRB Host 080517, summed over a 40 MHz bandwidth centred on the peak of the emission line. A + symbol marks the position of the GRB host galaxy, while an asterisk indicates the position of the neighbouring galaxy. Contours indicate the zero flux level (dotted) and +2 and 3 σ (solid). The 1 σ noise at the pointing centre of this map is 0.3 mJy beam⁻¹. There are no -2 σ peaks in the map. The large circle indicates the half-power extent of the PdBI primary beam. The ellipse at the lower left indicates the size of the synthesized beam.

efficiency of molecular gas conversion only reduce this timescale. The short implied gas consumption timescale suggests that the host of GRB 080517 is undergoing a short-lived star formation episode which is unlikely to add significantly to its stellar mass. This conclusion is consistent with the results of fitting the optical-near infrared spectral energy distribution, which required that the ongoing starburst contributed < 1% of the mass of the host galaxy, which is dominated by a more mature, 500 Myr-old stellar population (Stanway et al. 2014).

The width of the observed CO(1-0) emission line may lend tentative support to such a scenario. If the line width, $\Delta v = 77 \text{ km s}^{-1}$, is interpreted as Doppler broadening due to the stellar velocity dispersion, it implies a virial mass of just $1.3 \times 10^{10} M_{\odot}$. This must include the SED-derived stellar mass, $3.8^{+0.2}_{-1.2} \times 10^9 M_{\odot}$

(Stanway et al. 2014) and the gas content. The fraction of molecular relative to atomic gas in GRB host galaxies is poorly constrained, with existing measurements suggesting $\sim 10\%$ (Friis et al. 2014; Krühler et al. 2013) or lower (D’Elia et al. 2014) based on individual lines of sight probed by ultraviolet spectra of GRB afterglows. Our estimated molecular gas mass $M_{\text{H}_2} \sim 6.3 \times 10^8 M_{\odot}$ would therefore imply an atomic gas content similar to the galaxy’s stellar mass. Comparison with the virial mass suggests either that the host galaxy has very little dark matter, or that the line emission is not fully sampling the stellar velocity dispersion, as would be the case in a highly inclined disk galaxy or if the emitting gas has been recently accreted onto the GRB host and is not yet virialised.

Given the presence of a neighbouring galaxy, itself star-forming and sufficiently close in both projection and velocity to constitute an interacting system (Stanway et al. 2014; Ellison et al. 2008), it is tempting to speculate that the gas supply was accreted during a recent near fly-by of the galaxy pair. However, we caution that the current data has neither the signal to noise nor the spatial resolution to identify tidal features or other direct evidence of gravitational interaction. Alternate explanations remain plausible. There is evidence that the CO(1-0) transition may be sub-thermally excited in some galaxies with modest star formation rates (e.g. Daddi et al. 2014) at $z > 1$. These are typically higher in redshift and specific star formation rate and lower in metallicity than GRB Host 080517 (Stanway et al. 2014). Measurement of further rotational emission lines will be required to determine an accurate spectral line excitation ladder, and hence accurate gas temperature and mass.

Star formation in the local Universe is usually seen in relatively low mass galaxies compared to those at higher redshifts - the well-known ‘downsizing’ phenomenon (Cowie et al. 2004). Where star formation is observed in massive galaxies, it is typically accompanied by large molecular gas reserves. As a result the timescale for depletion of molecular gas, $\tau = M(\text{H}_2)/\text{SFR}$ in years, scales with the stellar mass of a galaxy (Bothwell et al. 2014).

As figure 3 demonstrates, the estimated gas mass and star formation rate places the host galaxy of GRB 080517 on the established gas-to-specific star for-

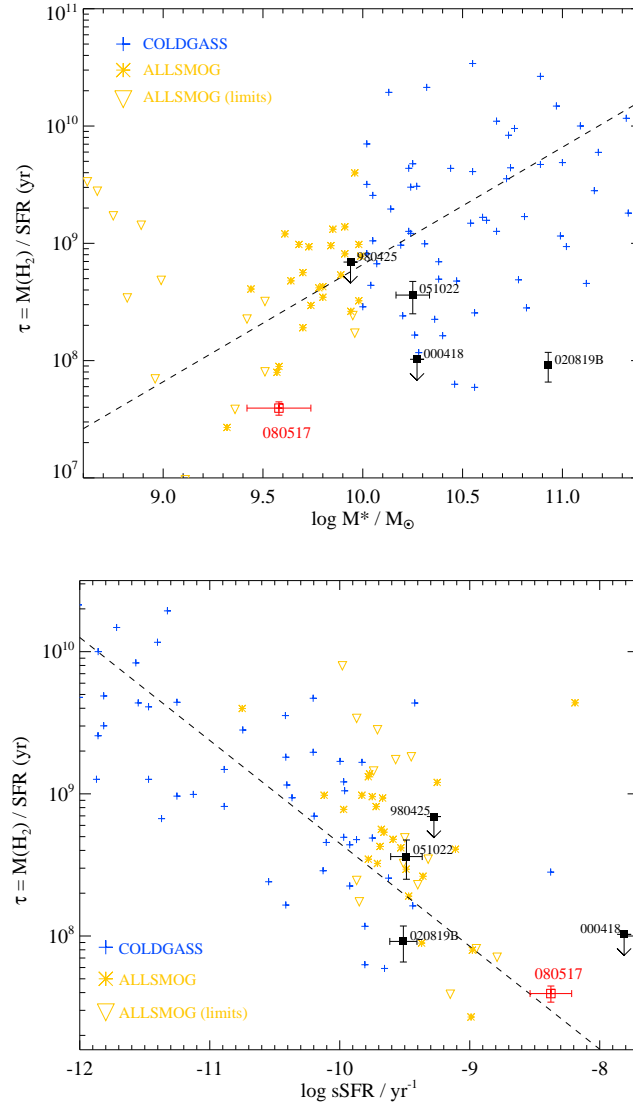


FIG. 3.— The timescale for molecular gas consumption (in years) for GRB Host 080517, compared to local galaxies from the COLDGASS (Saintonge et al. 2011a) and ALLSMOG (Bothwell et al. 2014) surveys. The dashed line marks the linear relation between stellar mass and depletion timescale determined by Bothwell et al. (2014) for those samples, and the relation between timescale and specific star formation rate determined by Saintonge et al. (2011b). We correct all literature values to our assumed CO-H₂ conversion factor, $\alpha=4.3$. Error bars combine 1σ uncertainties in all derived values. In common with other observed GRB host galaxies, GRB Host 080517 lies well below the mean gas depletion timescale in the local Universe for its mass, but is on the expected relation for its specific star formation rate.

mation rate relation (main sequence) for star forming galaxies in the local Universe, but well away from the predicted gas consumption timescale for its mass (Saintonge et al. 2011b; Bothwell et al. 2014). For comparison, we also mark the locations in this parameter space of those burst hosts with comparable CO measurements (Hatsukade et al. 2014, 2011; Endo et al. 2007), drawing stellar mass and star formation rate estimates from the literature (Perley et al. 2013; Michałowski et al. 2009) where necessary. We exclude the host of $z \sim 8$ burst GRB 090423 since it remains undetected in the continuum (Berger et al. 2014; Tanvir et al. 2012), as well as in molecular gas emission (Stanway et al. 2011).

The host of GRB 080517 appears to be typical of those GRB hosts observed to date. These all show short gas depletion timescales, below the relation derived by Bothwell et al. (2014) and Saintonge et al. (2011b) for

star forming galaxies in the local Universe. This is somewhat puzzling as a straightforward interpretation would imply that GRBs typically occur towards the end of a star formation episode, when little molecular gas remains. Such an interpretation contrasts with the assumption that they arise from massive stars, which collapse with only a short delay after the onset of star formation. An alternate plausible scenario is that the starburst giving rise to the GRB in these sources is a short-lived ‘flash in the pan’ event, not contributing substantially to the galaxy mass, as would seem to be the case for GRB 080517. This too would be a little surprising, since it implies that all the bursts observed in molecular gas to date fall into this category with the bulk properties of the host galaxy not representative of the brief star formation episode underlying the burst.

We note that our analysis represents an independent

confirmation of the molecular gas deficit seen in absorption line studies of GRB afterglows (see Tumlinson et al. 2007; Ledoux et al. 2009). It has been suggested that may be due in part to the low metallicity typical of burst hosts (Tumlinson et al. 2007; Ledoux et al. 2009) with resultant low dust content, or that detection of H_2 absorption requires significant depletion of refractory elements onto dust grains (Krühler et al. 2013), although the small spatial scales probed by absorption studies along a line of sight complicate these interpretations (Friis et al. 2014). It seems unlikely that metallicity is a strong factor in the short gas consumption timescales seen in figure 3. While all five bursts appear consistent with shorter timescales than typical for their mass, GRBs 980425 and 000418 are believed to be sub-Solar in mean metallicity, while GRBs 020819B, 051022 and 080517 are likely Solar or super-Solar (see Stanway et al. 2014; Hatsukade et al. 2014; Levesque et al. 2010; Svensson et al. 2010).

On the other hand, the role of depletion of metals onto dust grains may be significant. Of the bursts with CO detections, or deep limits, to date; GRBs 051022 and 020819B are classified as ‘dark’ bursts, their optical afterglows likely sub-luminous due to dust extinction (see Perley et al. 2013), and GRBs 080517 and 000418 show evidence for dusty conditions in their host galaxy (080517, Stanway et al. 2014) or afterglow (000418, Klose et al. 2000). The host of the low redshift, low luminosity GRB 980425, by contrast, is characterized by a low dust content overall, but with a high density environment associated with the GRB site (Michałowski et al. 2014). All five GRB hosts investigated to date, therefore, have dust properties somewhat atypical of the GRB population as a whole (see e.g. Svensson et al. 2010). Characterizing any association between extinction and gas depletion timescales will re-

quire larger, more complete samples. Obtaining these may be possible in the near future, utilizing the new sensitivity of ALMA for southern hemisphere targets. However, our observations with the (5-element) Plateau de Bure Interferometer demonstrates that detections of low redshift GRB hosts are possible with more moderate instrumentation.

5. CONCLUSIONS

We have identified only the third long GRB host galaxy to show observed emission from molecular gas. The integrated emission line flux of GRB host 080517, $SD\nu = 0.39 \pm 0.05 \text{ Jy km s}^{-1}$, suggests an estimated molecular mass of $M_{H_2} \sim 6.3 \times 10^8 M_\odot$. This leads to a remarkably short timescale for gas consumption in this system ($\sim 40 \text{ Myr}$) and, together with constraints from other wavelengths, suggest that the GRB occurred in a short-lived star formation episode that does not dominate the galaxy’s mass.

It appears that the GRB host galaxies observed to date show lower gas masses than might be anticipated from their mass and star formation rate, implying that building this sample in future may be difficult. While GRB 080517 is too far north for follow-up observations with ALMA, we have demonstrated that it is accessible with older, northern hemisphere arrays and that similar galaxies may be straightforwardly probed with current instrumentation.

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Facilities: PdBI

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